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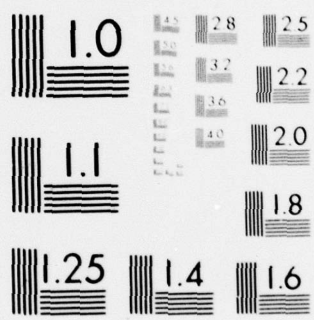

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PULSED HOLOGRAPHIC ANALYSIS OF LARGE VIBRATING VEHICLE COMPONENTS

JUN 1978

14p.

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INTRODUCTION

Double-pulsed holography provides a measurement technique for the analysis of large surface areas of vibrating components. A particular advantage of holography is that it requires no contact with the vibrating object, and it gives a solution to a classical problem in the area of both acoustic and vibration analysis. The surface of a vibrating object is represented by a series of fringes which connect points that have equal amplitudes of displacement. Since holography is based on interferometry, the accuracy is within a fraction of the wavelength of light.

Continuous wave (CW) holographic techniques, which utilize HeNe or argon laser light sources, are limited in a number of ways. The test object in CW holography has to be isolated from the environment because the maximum tolerable motion of the experimental apparatus is about an eighth of the laser light wavelength. CW holographic interferometric techniques are time-average and real-time holography, and they are restricted to the measurement of very small amplitudes. A maximum amplitude of displacement of about 25 wavelengths is possible using strobe light techniques such as acoustical optical modulators.

The difficulties in CW holography can be circumvented by the use of double pulsed holographic techniques. This work is based on results obtained by a Korad holographic camera, which employs a Q-switched ruby laser. Each laser pulse has a duration of twenty nanoseconds which is insignificant compared to the periods of vibrating structures. The pulse separation time usually varies between a few microseconds and about one millisecond while typical values usually range between 200 and 500 microseconds. Pulse separation time intervals are kept below one millisecond to avoid isolation problems with low frequency building vibrations but are still long enough to record surface displacement occuring at the frequencies of interest. In any case the pulse separation times are much shorter than the periods of the vibration frequencies for large amplitude displacement.

PULSED RUBY LASER

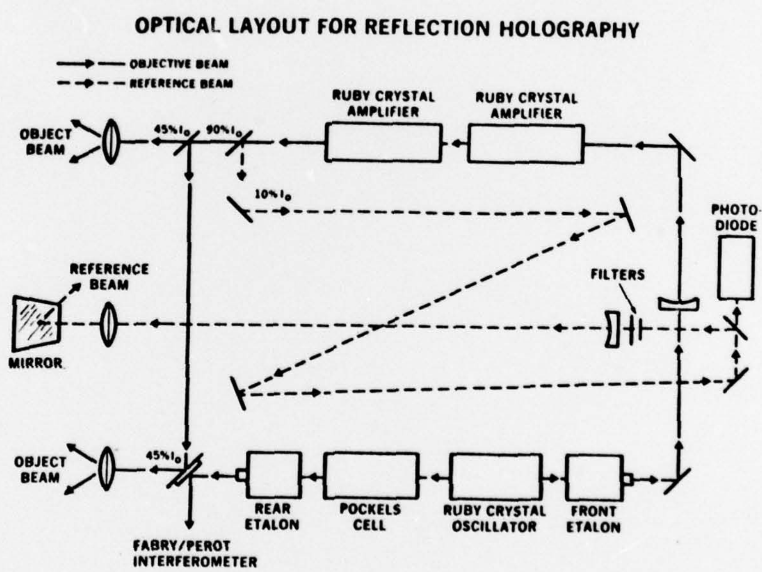

Figure 1

Figure 1 shows a diagram of the pulsed holographic camera which is used for our data acquisition. The laser oscillator is located at the bottom of Fig. 1 and it produces a low energy light pulse of a few millijoules. The oscillator cavity consists of a front and rear etalon, pockels cell, and ruby rod. The two etalons each contain some Fabry-Perot elements and are individually tuned by controlling the temperature to within a tenth of a centigrade degree. Individual resistive heating elements with the appropriate control circuits are used to maintain a very uniform etalon temperature over relatively long time intervals. In addition the etalons are in protective housings which will insulate them from the ambient temperature. The pockels cell is used to Q switch the oscillator and provide two output pulses of equal amplitude. The etalons are tuned so that the ratio of front-to-rear output energy is a maximum. The output from the rear etalon is diverted into the Fabry-Perot interferometer. The ruby rod is also temperature controlled by a separate water cooled unit to within 0.1C.^{o} Special anti-reflecting coatings are on the rod surfaces so that the cavity length is determined by the two etalons. The rear etalon has four elements, and it is designed so that the oscillator cavity modes have a high finesse and a very narrow line width for long temporal coherence lengths. The front etalon has a single quartz element and is tuned for maximum output.

The output from the oscillator is diverged by a negative lens before entering the first of two ruby amplifiers. The output from the ruby power amplifiers consists of two pulses with up to two joules per pulse that passes through a beam splitter. Ten percent of the light energy is reflected into the reference beam while the remaining 90% is equally distributed between the two object beams. These beams then pass through diffusers in order to obtain a uniform illumination of the object. The amplifier output beam energy is monitored by sampling a part of the reference beam with a calibrated photo-diode. The reference beam passes through a two meter delay line and uniformly illuminates the holographic plate.

Figure 2 shows the holographic camera head. The circular window in the side cover allows the beam from the rear etalon to pass through to the Fabry-Perot interferometer which is not present in this photograph. The plate holder is shown at the top with an electronic shutter which is synchronized with the pulse trigger. The two object ports are shown in front along with the reference beam mirror housing.

Figure 3 shows a side view of the laser head with the Fabry-Perot interferometer mounted on the left side. The ruby oscillator is clearly displayed along with the high voltage cables and cooling lines.

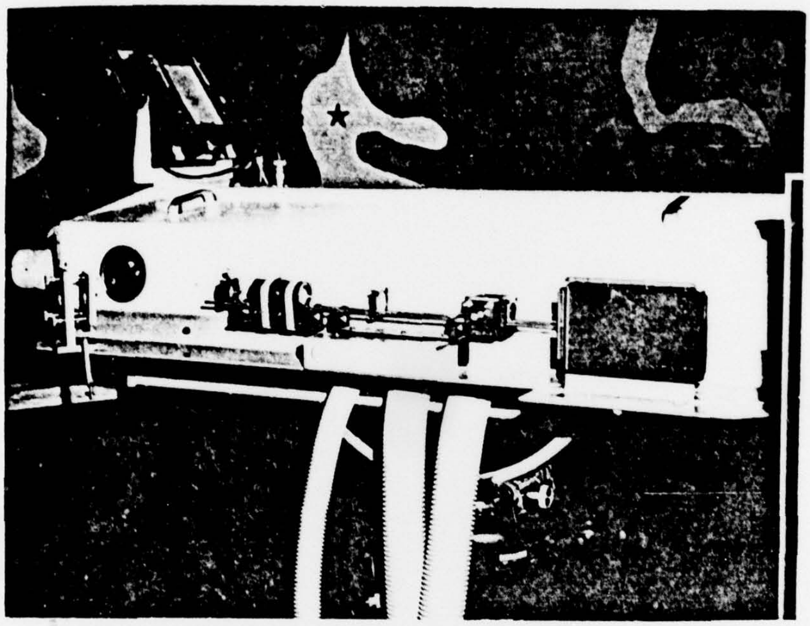

Figure 2

Figure 4 contains two instrumentation racks which house various power supplies and pulse shaping components. The left rack contains two 10KV power supplies for the ruby amplifiers and the oscillator flash lamps. The right rack also contains two 10KV power supplies for pulsing each side of the pockels cell to obtain the double pulse output. An additional component in this rack is a digital pulse generator which sets the pulse separation time between each of the output pulses. Also in Figure 4 are a storage oscilloscope for displaying the photo diode outputs and two digital thermometers for monitoring the temperature of the etalons and the ruby rod.

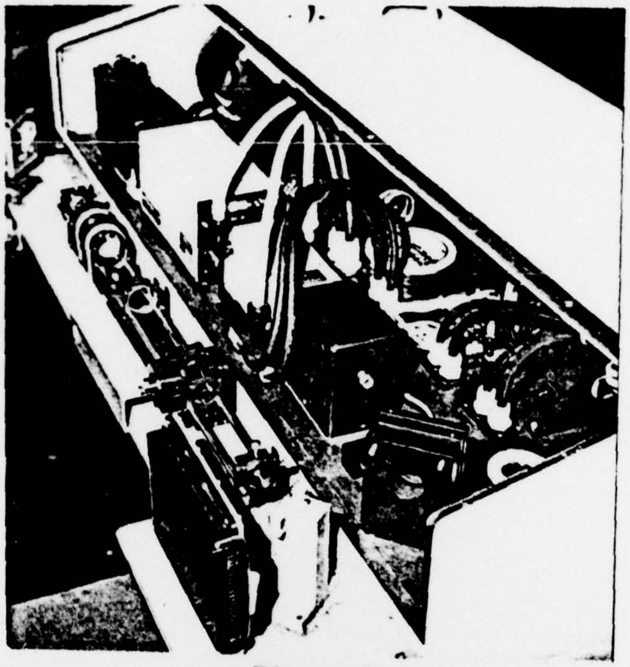

Figure 3

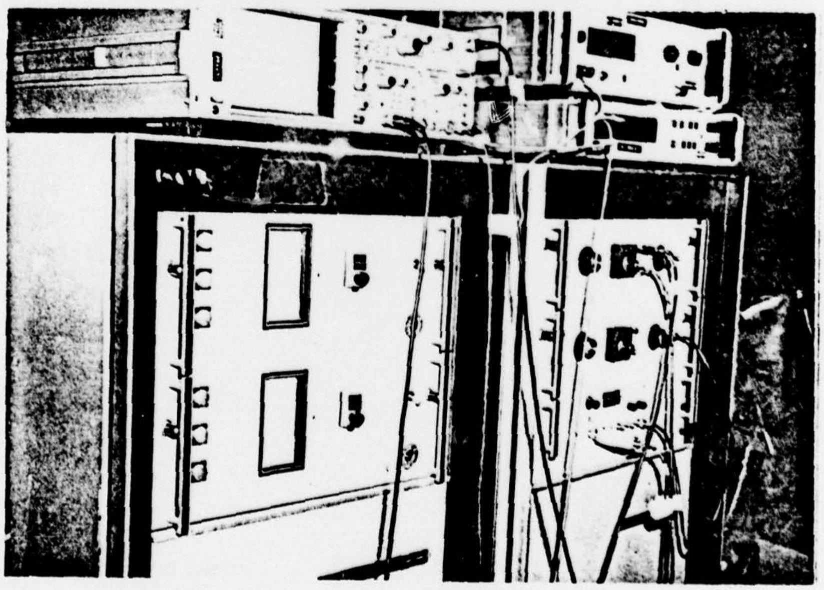

Figure 4

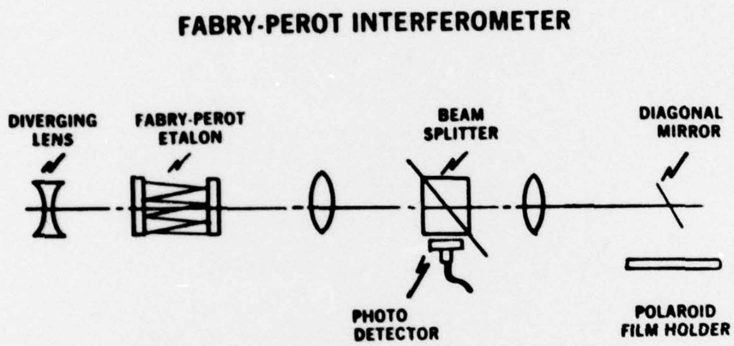

Figure 5

Each point of the illuminated object reflects a portion of the laser light back onto a photographic plate as shown in Fig. 1. Since the object and reference beams are coherent, an interference pattern is created on the photographic plate. A hologram is a photographic place which contains both the amplitude and phase information of the reflective wave from the object. A virtual image of the object is then reconstructed by illuminating the hologram with light from a HeNe gas laser.

In double pulse holography two consecutive exposures of a vibrating object are made on the same photographic plate. These exposures are coincident with the double pulse output of the ruby laser and record information about the position of the vibrating object at the two distinct times. The interference between these diffraction patterns during reconstruction gives rise to the fringe pattern.

RUBY LASER COHERENCE REQUIREMENTS

The ruby laser must have a coherence length of at least one meter and preferably closer to 7 meters. The coherence limitation of our system is temporal and not spatial. A temporal coherence of 7 meters for a double pulse laser implies that both pulses must oscillate on the same cavity mode. The coherence length is reduced to one meter if the laser pulses are of equal intensity and located on adjacent cavity modes. The laser cavity contains components for longitudinal and transverse mode selection to achieve long coherence-length pulses. The rear etalons (Fig. 1) contain numerous elements to suppress longitudinal mode components. The output energy from the ruby laser oscillator is drastically reduced after mode selection. The laser is tuned to oscillate in the TEM_{00} mode just above an energy threshold of about 5 millijoules per pulse. The laser output is Q-switched to produce a pulse width of 20 to 30 nanoseconds. The peak power from the double stage amplifier output is 100 megawatts.

The coherence length between each of the two pulses can be monitored using a Fabry-Perot (FP) interferometer (Fig. 5). The FP unit is mounted on a bracket alongside of the holographic camera as shown in Fig. 3. The FP interferometer consists of a FP etalon, a diverging lens, and a Galilean telescope with a magnification of about 15. A Polaroid camera back records the FP interference pattern which consists of circular rings of various orders. The laser output is multi-moded if the various interference orders have a multiple structure. Fig. 6a shows a FP interference pattern for a double pulse, single mode laser output. Each of the diffraction orders is a singlet and the relative temporal coherence of the two pulses is greater than 7 meters. Figure 6b shows a FP interference pattern where the output energy is distributed over several cavity modes. The temporal coherence of this double pulse shot is only a few centimeters.

A great deal of operator skill and tuning is required to maintain a 7 meter coherence length for double pulse operation. Temperature effects are very important and a temperature controlled laboratory is a must for consistent results.

Figure 6a

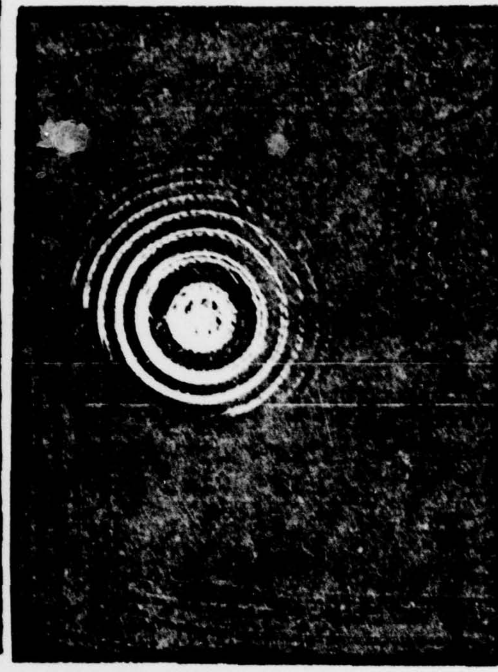

Figure 6b

A CALCULATION OF THE VIBRATION AMPLITUDE

Consider a point on the surface of a vibrating object which is illuminated by two pulses from a ruby laser. The pulses are of equal intensity and separated by a time interval which is small compared to the period of oscillation T. The point on the surface moves a distance d during T and generates a phase difference ϕ between the two object points as shown in Fig. 7. The optical path difference between the two object waves is given by the amount

$$d = d(\cos\alpha + \cos\beta), \qquad (1)$$

where α and β are the angles of illumination and reflection with respect to the surface normal. The phase difference ϕ is

$$\phi = \frac{2\pi d}{\lambda} (\cos\alpha + \cos\beta), \qquad (2)$$

where λ is the wavelength of the ruby laser. Each object wave interferes with the reference beam to produce a separate hologram on the photographic plate.

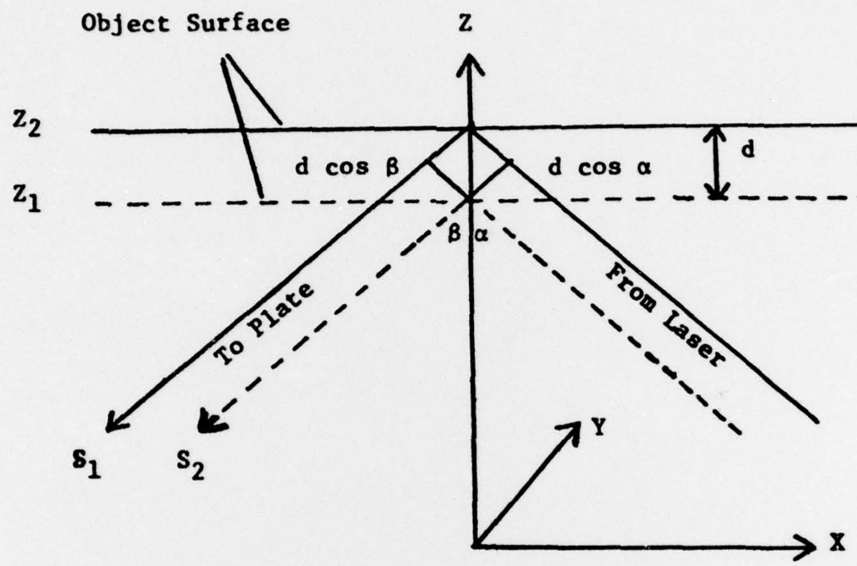

Figure 7

The superposition of the two exposures during reconstruction yields a series of fringe lines. A minimum in intensity is obtained if

$$d_{min} = \frac{(2n + 1)\lambda}{2(\cos\alpha + \cos\beta)} \tag{3}$$

where n is a positive integer. Points of equal displacement are connected by interference fringes, and the relative deformation of the object surface is determined by the contour and spacing of the holographic fringes. The spacing between n interference fringes gives the component of the displacement normal to the surface as

$$d_{max} = \frac{n\lambda}{(\cos\alpha + \cos\beta)}. \tag{4}$$

The relative displacement between the two object points is determined by counting the interference fringes between these points.

The average surface velocity is the relative displacement divided by the pulse separation time Δt, and it is proportional to the density of holographic fringes.

A double exposure hologram is used to measure the amplitudes of vibration. A transducer which is attached to the area of interest provides the trigger signal for the laser pulses. Any part of the period of oscillation can be examined by employing electronics delay circuitry. The relative timing of the laser pulses and the oscillation of the object point is shown in Fig. 8.

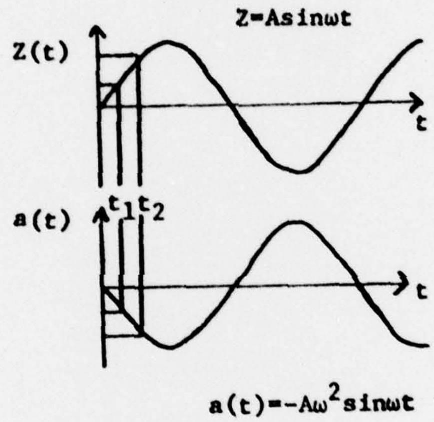

Figure 8

The displacement $Z(t)$ of the object surface at times t_1 and t_2 is given by

$$Z(t_1) = A \sin \omega t_1$$

$$Z(t_2) = A \sin \omega t_2$$

$$d = Z(t_2) - Z(t_1), \tag{5}$$

where ω is the oscillation frequency of the object point. The amplitude A is determined by substituting Eq 5 into Eq 3. Amplitudes of any magnitude can be determined at the object point by using this technique.

DISCUSSION OF EXPERIMENTAL RESULTS

A detailed analysis of three holograms will be discussed in this section. A 15 milliwatt helium-neon laser was used to reconstruct the virtual holographic images which were quite bright and easily viewed with the naked eye. These images were photographed with Polaroid 4 by 5 inch type Positive/Negative film. A 105 mm telephoto lens with a F16 stop gave quite good results. The contrast ratio of the holographic fringes was better than the photographic film; consequently, the photographs are not as good as the holographic images. The photographs are also inferior because of their limited depth of field and field of view.

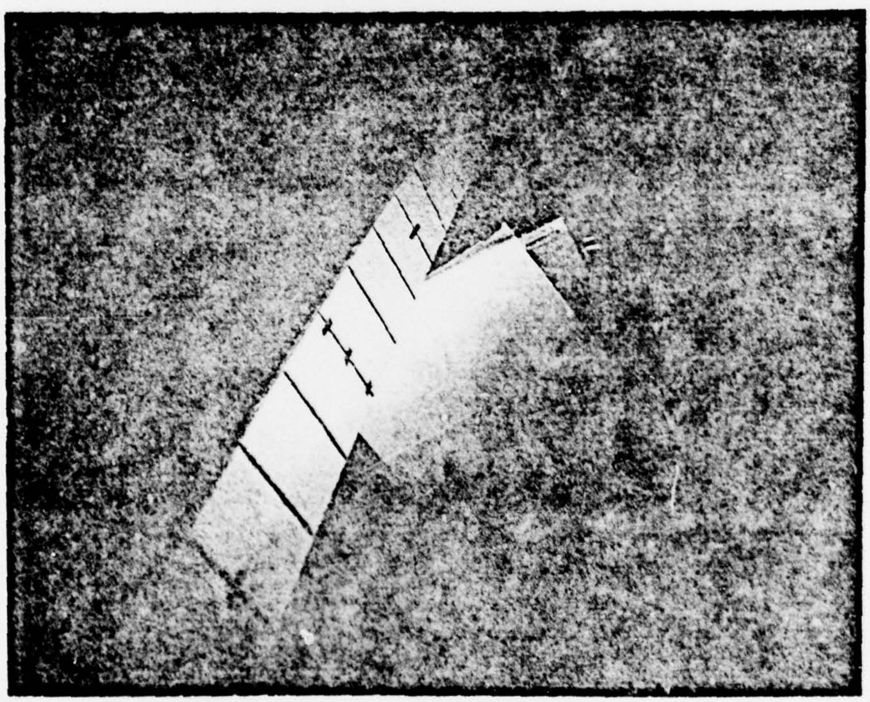

Figure 9

Figure 9 is a photograph of a single pulse, single mode hologram with a 3.5 meter calibration board extending across the field of view. The black lines on the board are approximately 20 cm. apart and about 75% of the board is visible in the photograph. The entire board is visible in the actual holographic image in addition to the wall in the background. The hologram has at least seven meters coherence properties since no localized fringes are visible along the entire extent of the board.

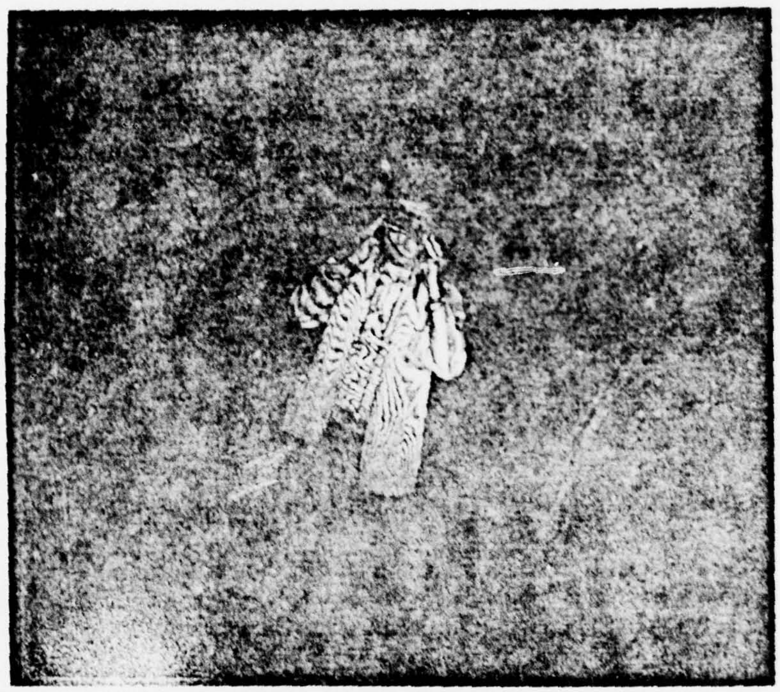

Figure 10

Figure 10 is a photograph of a seven meter double pulse hologram of a man standing 2 meters in front of the holographic camera. The man is apparently motionless to the unaided eye; although, many fringes exist in the holographic images. The tiny muscle movements of the human body are clearly visible via the fringe contours, and the regions of highest fringe density are regions of largest amplitude of vibration. The fringe contrast in this hologram is excellent because the two ruby pulses have nearly identical amplitudes. The pulse separation time between the two laser pulses is about 500 μ sec.

Figure 11

Figure 11 is a photograph of a double pulse hologram of a vacuum pump. The fringes are caused by an internal vibration due to the motor running at a normal rate. The pump is painted white to increase the fringe contrast and the pulse separation time is 300 μ sec. The parallel fringes on the baffle and the intake tube are caused by a cantilevered motion of these parts. The bulls eye patterns on the base and the side panels are due to mode excitations on these respective regions of the pump.

None of the double pulse holograms were synchronized with the vibrational motion of the object. The ruby laser was manually triggered so that the fringe pattern varied depending upon the relative phase between the trigger pulse and the object motion. The fringe contours remained relatively constant in shape; although, the fringe intensity at a fixed point on the object varied randomly between light and dark. In the future we intend to externally trigger the laser off of an accelerometer transducer which is fixed on the object. The fringe contour and spacing will remain constant if the system parameters are unchanged from one hologram to the next. This procedure will help standardize the variation in fringe pattern which is caused by real structural changes in the object.

The holographic camera in its present configuration is a very temperamental piece of instrumentation. The main problem seems to be one of temperature stabilization. If the laboratory temperature varies by more than 5 Celsius degrees, the laser output becomes unstable. Since the oscillator must operate so close to threshold, small variations in cavity length or element spacing in the etalons rapidly detunes the system. The etalon temperatures seem to be well controlled by resistive heaters which are positioned on the mirror mounts. The most likely problem at this time is the temperature variations in the aluminum baseplate. Work is in progress at Korad to mount the oscillator on an invar base plate. Since the oscillator components are bolted directly to the base plate, the much smaller thermal expension coefficient of invar should minimize this effect. Another approach is to put resistive heaters on the current aluminum base plate and heat it above the ambient. The base plate will be insulated from the ambient and its temperature will be controlled to within 1 centigrade degree. A last resort would be to put the oscillator in a precisely temperature controlled oven and insulate it from the ambient. This approach would be quite expensive and involve a considerable redesign of the present holographic system.

Pulsed holography promises to be a very exciting and useful tool for investigating the vibration characteristics of mechanical structures. The fringe pattern gives the design engineer a visual picture of regions on the structure with large displacement amplitudes, large stress concentrations, and the position of nodes and anti-nodes of vibration. The state-of-the-art ruby lasers have large energy outputs that enable the holographer to illuminate sizable surface areas on the test specimen. The basic limitation is that at present the technique is suitable only for laboratory environments. The tight temperature specifications of the oscillator would make routine double pulse holography difficult in a production line environment.